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A METHOD FOR PREDICTING THE GAS PROPERTIES SURROUNDING AEROSPACE VEHICLES IN SUPERSONIC OR HYPERSONIC FLIGHT

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Summary

This paper describes two computer programs which have been combined to obtain inviscid perfect and real gas flow fields around axisymmetric blunt nosed vehicles at zero angle of attack, at supersonic or hypersonic flight velocities (Reference 1). A blunt body computer program which calculates the subsonic portion of the flow field, and a method of characteristics computer program which determines the supersonic portion of the flow field, were integrated into a combined efficient single automatic computer program. The blunt body program's output automatically supplies the method of characteristics program with the necessary input it requires. The two programs were made mutually compatible and were physically linked together. The linking of the two programs is described.

A drag calculation subroutine is described which was developed to integrate the pressure distribution on the body, in order to determine the total drag and drag coefficient of the body. A geometry subroutine was also developed to extend and improve the body geometry capability so as to include arbitrary aerodynamic body shapes.

This program is required for vehicle design and analysis since these flow fields must be determined in order to make predictions of vehicle performance. Specifically, the program is necessary for determining vehicle body surface conditions which are used for:

- 1 Calculating aerodynamic coefficients (drag),
- 2 Calculating body loads,
- 3 Correlating wind tunnel data, and
- 4 Calculating vehicle thermodynamics (heat transfer).

The program is also needed for calculating the perfect or real gas properties in the shock layer surrounding the vehicle which are useful for predicting:

- 5 Vehicle control system effectiveness when using control surfaces, jet interaction or external burning control techniques,
- 6 The electromagnetic gas properties required to predict the degree of communications attenuation or blackout through the hot plasma sheath, and
- 7 Airbreathing propulsion system inlet conditions.

This program eliminates the use of existing approximation methods and programs that do not adequately describe the perfect gas body surface conditions. Also, at present, there are no other methods available for describing the real gas body surface conditions or predicting the gas properties in the shock layer surrounding the vehicle, which are necessarily required to accomplish items 1-7 above.

One big advantage of the combined program described, lies in the fact that it was designed such that a blunt body solution does not have to be rerun due to a design change in the afterbody shape, i.e.; one nose may be run with a series of afterbodies (body shapes) thereby consuming less computer run time and reducing design analysis cost. Body shapes and flight conditions run thus far have been tabulated and catalogued.

Using the combined program, exact inviscid numerical solutions can be obtained for the steady-state perfect gas and real gas flow fields around axisymmetric blunt nosed missile configurations, at zero angle of attack. Flow fields were generated for many configurations using the combined blunt body and method of characteristics programs over a wide range of Mach numbers. Spherically-capped conical bodies, power law bodies, ogives, and other aerodynamic shapes were run over a Mach number range from 3 to 10. These results obtained using the computer program, for several missile configurations, have been compared with other analytical techniques and experimental data. In particular, comparisons of body surface conditions were made with second-order shock-expansion theory and modified Newtonian theory. These results will be presented on slides at the

meeting and will be presented and discussed in a subsequent paper.

This present paper gives the capabilities of the computer program, limitations and restrictions, conclusions and recommendations, and areas of future work. Information is also given on the theoretical analyses and techniques employed, the input data obtained, and information on the computer program general operation and utilization. The results of an industry wide survey of the state of the art are also presented.

I. Introduction

A. Background

Prior to the outset of this work there were virtually no techniques available at the Martin Marietta Corporation for the exact calculation of inviscid missile flow fields. Techniques were nonexistent even for the symmetric case of missile flight at zero angle of attack. Only approximate methods were available for calculating local flow or body surface conditions for ideal gas flow, and none were available for determining real gas flow fields. However, this information from exact flow field calculations is necessarily required for making accurate predictions of vehicle aerodynamics and thermodynamics. Also, there were no methods available for calculating either the ideal gas or real gas aerothermodynamic variables in the shock layer surrounding the vehicle which are required for predicting vehicle control surface effectiveness, electromagnetic wave (radar) attenuation resulting in communications blackout, and the optimum location for airbreathing propulsion system inlets.

These factors led to the requirements for the development of a computer program which could determine the ideal and real gas flow fields about blunt nosed missile configurations at zero angle of attack.

The author conducted an industry survey for the purpose of determining the present state of the art. The highlights of this survey will now be discussed.

B. State of the Art

Howard Lomax at NASA-Ames has continuously improved its Van Dyke blunt body program over the past several years under NASA sponsorship. Lockheed utilizes the Lomax version of Van Dyke's inverse blunt body technique when running flow fields for bodies not much blunter than a sphere, traveling at suborbital (ballistic) velocities. For flights at superorbital or reentry velocities Lock-

heed uses a thin shock layer analysis developed by Dr. S. Maslen of Martin Marietta Corporation. Maslen's method was developed further by Dr. Hoshizaki at Lockheed's Palo Alto Research Laboratory. Specifically, he added more physics and chemistry by including such phenomena as radiation, ionization, and viscous effects. This analysis is presently being modified under NASA sponsorship to handle bodies at angle of attack. Lockheed also uses Dr. Rudolph Swigart's blunt body computer program, which uses a semi-analytic technique called the method of series truncation. Dr. Raul Conti of Lockheed has extended Swigart's method to include nonequilibrium real gas flow. It should be noted that Lockheed's Lomax blunt body program does not operate below a flight Mach number of four (M^4). For lower flight Mach numbers, Swigart's program is used. Note: Orlando Division's Van Dyke blunt body program described herein does not have this low Mach number restriction. Lockheed uses its own method of characteristics program.

Mr. Sid Powers at Northrop utilizes a Van Dyke method blunt body computer program. Orlando Division's blunt body computer program described in this report is a slight variation of this program which was developed for the Air Force's Flight Dynamics Laboratory. Northrop has demonstrated its program under contract to the Office of Naval Research in conjunction with several aerospace companies, government agencies, and educational institutions. On a contractual basis, each organization was asked to provide four blunt body flow fields for comparative purposes. Norair ran these cases on its IBM 7090 digital computer. The results are presented in Final Report NOR 64-309 dated 23 December 1964. Other contractors involved were Douglas, Avco, General Electric, Lockheed, NASA, MIT, Naval Weapons Laboratory (NWL) and Naval Ordnance Laboratory (NOL). These analytical results were compared to experimental results and reported in NOL TR 66-138 dated 5 July 1966. Many of the contractors had difficulty in making the required runs. In particular, they had difficulty in obtaining sonic lines and generating starting lines.

Norair has two method of characteristics programs which it uses in conjunction with its blunt body program. One is an axisymmetric program developed under company funds (and is therefore proprietary) and the other is a three-dimensional method of characteristics program presently being developed under Air Force Flight Dynamics Laboratory Contract.

Space General Corporation uses a variation of the NASA-Lomax blunt body computer program, which was developed further under contract to the

Air Force Flight Dynamics Laboratory in conjunction with a method of characteristics program developed at Aerojet General Corporation which is the program used at the Martin Marietta Orlando Division as described in this report.

General Applied Science Laboratories (GASL) has made several new revisions and additions under a present AMICOM contract to its three-dimensional method of characteristics program originally developed under Air Force, ARPA, Sandia Corporation, AEC, and AMICOM funding. These revisions, improvements, and additions include:

- 1 The existing blunt body inverse method was replaced with a direct method solution developed by Gino Moretti of GASL (Reference AIAA Journal, May 1967) which is a faster and more accurate solution.
- 2 A method was provided for starting the 3-D method of characteristics program with a sharp conical body at angle of attack to be used in lieu of the blunt body starting solution. This program has real gas capability, but cannot be used in conjunction with the boundary layer program, or the secondary shock capability.
- 3 Secondary shock capability was added to the 3-D method of characteristics program to calculate the flow properties past compression corners and on flares on blunt nosed bodies of revolution at angle of attack.

As a result of the industry survey described above, it was decided that it would be more expedient to obtain and modify existing programs to develop the capability required, rather than to write completely new programs. It was the author's opinion that the writing of new programs would require considerable time and effort, and would only represent a further duplication of effort. Therefore, two programs were obtained by the author from the U.S. Army Missile Command (AMICOM). The two programs obtained were:

- 1 A blunt body program developed by Northrop Corporation, which is described in Section II,
- 2 A method of characteristics program developed by Space General Corporation, which is described in Section IV.

These programs were made mutually compatible and were integrated into one efficient computer program. The integration or linking of the two

computer programs is described in detail in Section III.

A drag calculation subroutine which integrates the body surface pressure distribution to determine vehicle wave drag, and drag coefficient, is described in Section V. A geometry subroutine was written to increase the geometry capability of the program. Flow fields for many shapes can now be obtained. The blunt body program will now be described.

II. Subsonic Blunt Body Program

A. General Description

The blunt body portion of the present computer program was developed for the Air Force Flight Dynamics Laboratory by Northrop. The technique employed was developed by Van Dyke (Reference 2). An inverse method is used to calculate the subsonic inviscid flow field around a body downstream of the bow shock wave.

The program is written in Fortran IV. It computes the subsonic portion of the flow field around the spherical cap of any spherically capped missile body over a wide range of Mach numbers. Although the program has been run at Mach numbers as low as $M = 1.2$ and as high as $M = 15.0$, the program is most useful in the Mach number range from $M = 3.0$ to $M = 10.0$.

The program is fast and automatic. The only input quantities required to run the program are the free stream conditions.

The subsonic blunt body program was modified to compute and provide a supersonic starting line which is stored on tape and punched on cards. This output was made compatible with the input required for the supersonic method of characteristics program. The method of characteristics program calculates the supersonic portion of the flow field around the missile as described subsequently in this paper.

B. Analysis

The procedure used in calculating the subsonic inviscid flow field downstream of the bow shock wave is generally referred to as the inverse method. In this technique, a shock wave shape is chosen and the equations of motion are integrated by finite differences to obtain the corresponding body shape desired. The inverse technique employed is essentially that developed by Van Dyke (Reference 2).

The program compares the computed body shape, and iterates until the desired shock wave shape is found. The technique consists of a straight-forward numerical integration of the equations of motion proceeding downstream from an assumed shock wave shape described by a conic section.

In cylindrical polar coordinates (r,x) originating from the shock wave's vertex, any such shock wave is described by the equation:

$$r^2 = 2 R_g x - B_g x^2$$

where R_g is the nose radius of the shock (taken to be equal to one in the computer program) and B_g is the shock bluntness, a convenient parameter that characterizes the eccentricity of the conic section. The value for the shock bluntness B_g for the paraboloidal shock shape associated with the spherically capped body shapes considered in this paper is zero.

The differential equations, initial conditions, and numerical solution of the equations using a finite difference scheme, are discussed in detail in References 2 and 3.

C. Capabilities

The blunt body program provides the subsonic flow field for the spherical nose geometry over a wide range of free stream Mach numbers ($M = 1.2$ to $M = 15$).

The program prints out the subsonic flow field solution for both the local body conditions and the conditions in the shock layer (i.e., all of the flow variables at each point), the location of and the flow variables on the sonic line, and the starting line necessary to start the method of characteristics program for the calculation of the supersonic portion of the flow field.

D. Limitations and Restrictions

In several isolated cases, an instability in the pressure and Mach number distribution occurred on the body. This problem might possibly be alleviated by changing the computational mesh size. This can be accomplished by revising the number of steps (lines) or revising the number of points to be calculated on each line. Both the number of steps and the number of points are input. A systematic parametric study (series of runs) may be conducted to determine the optimum number of steps and points which represent a tradeoff between accuracy and minimum computer run time.

E. Input

Input to the program consists of basically the flight conditions (specifically free stream pressure, temperature and Mach number), the gas model to be employed (ideal or real gas) and the computational mesh size.

F. Output

The output consists of the subsonic flow field (including the data on the body and behind the shock wave), and a small portion of the supersonic flow field.

The blunt body program calculates and prints out the shock detachment distance, the body bluntness (equal to one for the spherical cap), the body radius (nondimensionalized with respect to the shock wave radius), and the flow field in its entirety, including points on the shock wave, the intermediate flow field and the body, and the aerothermodynamic parameters associated with these points.

Specifically, every point in the flow field will have the following flow variables associated with it:

- 1 X-distance, nondimensionalized with respect to shock-radius (equal to 1)
- 2 Y-distance, nondimensionalized with respect to shock-radius (equal to 1)
- 3 Mach number
- 4 Flow angle in degrees
- 5 Shock angle in degrees (only appears for shock wave)
- 6 Number of iterations to find point
- 7 Electron concentration
- 8 Velocity in ft/sec
- 9 Pressure in atmospheres
- 10 Temperature in °K
- 11 Density ratio, nondimensional ($\rho/\text{free-stream density}$)
- 12 Z, compressibility factor

- 13 Entropy, nondimensional
- 14 Enthalpy, nondimensional.

After the entire flow field is complete, an interpolation is performed to determine a sonic (actually slightly supersonic) starting line needed as input for the method of characteristics program as described in Section III. The resulting starting line is printed out by the blunt body program. The variables printed out are:

- 1 X, nondimensionalized with respect to body nose radius (in body coordinates)
- 2 Y, nondimensionalized with respect to body nose radius (in body coordinates)
- 3 Velocity in ft/sec
- 4 Flow angle in degrees
- 5 Pressure in lb/ft²
- 6 Density in slugs/ft³
- 7 Mach number.

III. Communication Between the Blunt Body and Characteristics Programs

A. Starting Line

The primary function of the blunt body program is to compute the subsonic flow field about a missile body. In addition, the blunt body program must generate a sonic starting line which will be used to initiate the method of characteristics program which calculates the supersonic flow regime. The starting line consists of 16 equally spaced points. Associated with each of the 16 points are the following parameters: x, y, velocity, flow angle, pressure, density and Mach number. This starting line is determined in the following manner. The blunt body program assumes some shock shape and solves for the body determined by this shock shape. The actual body obtained will consist of approximately 30 points. A general least squares curve fit is made through these points. The coefficients determined by the curve fit are used to compute the body radius, the shock detachment distance, and the body bluntness. This body bluntness is compared with the desired input bluntness (equal to 1 for a sphere). If the two are within the input tolerance, then a solution has been obtained. The problem is not yet complete, however. The entire flow field consisting of points on the shock wave, the interior flow field and the body are not written out until the body has converged. Subsequently (after convergence) the

shock parameters are readjusted and the entire field is calculated again from the shock wave to the body. This additional iteration serves three purposes:

- 1 It increases the accuracy of the computations and thereby gives a better body shape
- 2 This last iteration allows the entire flow field to appear as output (not just the body points as in previous iterations)
- 3 During the last iteration the entire flow field is also written on magnetic tape (in addition to the print-out).

This tape is written in order that the starting line may be generated. A point in the flow field is selected which satisfies two criteria:

- 1 It must have a local Mach number equal to or slightly greater than one;
- 2 It must have the largest value of Y/X of any other point satisfying 1.

A line is constructed through this point and the center of the sphere. The 16 starting line points are determined using a fourth-order interpolation. The flow variables on this starting line are required as inputs to the method of characteristics program.

B. Linking of Blunt Body and Method of Characteristics Program

The linking of the blunt body and method of characteristics program is accomplished through the use of two subroutines IVL and ESPAC. These subroutines provide information, and in particular, the so-called starting line necessary to initiate the method of characteristics calculation in the supersonic portion of the flow field. They provide the initial values for the method of characteristics program, and equally spaced points on the starting line which assures a more uniform characteristic net.

However, it should be noted that equally spaced points are desirable for the higher Mach numbers (hypersonic) but cause problems at the lower Mach numbers (supersonic, where $M < 3$), resulting in imbedded shocks as described in the section on limitations.

These two subroutines essentially link the two major subprograms (the blunt body subprogram and the method of characteristics subprogram).

C. Subroutine IVL

The purpose of this subroutine is to determine the initial values (starting line) for the method of characteristics program. IVL reads in the entire flow field from a tape which has been generated by another subroutine. Each point on the tape has six parameters associated with it: X/R_s , Y/R_s , flow angle (degrees), Mach number, pressure (atmospheres), and entropy S/R . A point is then selected from the flow field with the following properties:

- 1 The point is supersonic;
- 2 A line drawn through this point and the center of the sphere will have no subsonic points on it.

The straight line between this point and the sphere's center is the starting line. Points in the vicinity of this line are then stored and routine ESPAC is called.

D. Subroutine ESPAC

This routine applies a fourth-order interpolation routine to the points stored in IVL to determine a 16 point, equally spaced, starting line. In addition, changes in units and flow variables are affected through use of this routine to attain compatibility with the input requirements of the method of characteristics program.

E. Subroutine PUNCH

A subroutine called PUNCH was developed to punch the resulting starting line on cards so that a blunt body run for a given flight condition does not have to be repeated when used in conjunction with several different vehicle configurations. These cards can be used to start the method of characteristics program together with the cards describing the particular geometry or body shape. Only the latter must be changed to obtain flow fields for different body shapes, thereby conserving digital computer machine time which becomes an important factor in obtaining parametric data and information.

F. Transformation of Coordinates Between Shock and Body Coordinates

The blunt body program makes all x , y computations relative to the radius of the shock, R_s which is taken to be 1. The method of characteristics program requires that all x , y locations be nondimensionalized relative to (i.e., nondimensionalized with respect to) the body nose radius R_b . This necessitates changing the x 's and y 's in going

from program to program since not only are the radii of the shock and body different, but the origin of the shock and body coordinate systems are not coincident. Hence, in order to transfer from shock coordinates to body coordinates the following transformation is needed:

$$Y = \frac{y}{R_b} = \frac{y}{R_s} \frac{R_s}{R_b};$$
$$X = \frac{x}{R_b} = \left[\frac{x}{R_s} - \frac{\Delta x}{R_s} \right] \frac{R_s}{R_b}$$

where $\Delta x/R_s$, R_s/R_b , x/R_s , and y/R_s are the actual output of the blunt body program. Note: Δx is the shock detachment distance.

IV. Method of Characteristics Program

A. General Description

The method of characteristics program is used to determine the flow properties (i.e., velocity, flow angle, enthalpy, entropy, temperature, pressure, density, and Mach number) at each point in the inviscid supersonic portion of the flow field. The flow properties are determined behind the bow shock, in the shock layer, and on the axisymmetric missile body contour over which the flow is passing.

B. Analysis

The following assumptions are used in the method of characteristics analysis:

- 1 The stagnation enthalpy in the flow field is assumed to remain constant
- 2 The entropy along a streamline is assumed to remain constant
- 3 The flow is assumed to be steady (i.e., there is no time dependence)
- 4 The flow is assumed to be either calorically perfect, or, a real gas is considered.

The derivation of the conservation equations, the differential equations for the characteristics, and the geometrical equations utilized are described in detail in Reference 4. Also, detailed descriptions of the calculations for interior points, points along the shock wave, and points on the body are given.

C. Capabilities

The method of characteristics program can handle various afterbody geometries such as

conical frustums, ogives (circular arcs), power bodies, or L-D Haack and L-V Haack afterbodies.* These afterbody sections can be used in combination to describe any arbitrary missile shape. The free-stream Mach number range over which the program operates successfully is $M \geq 3$.

The program is automatic, and requires only a starting line which is supplied by the blunt body program and the body geometry.

The program first fills in the flow field between the starting line and the body, generating left running characteristics until the shock wave is reached. Then, a point on the shock is found and a new left running characteristic is generated to the body. This process continues until either the program completes the flow field or until 200 points have been generated along the shock wave.

However, careful matching of the surface slopes between the blunt body solution and the start of the characteristics solution is necessary. Care must be taken to ensure that the body shape is continuous. The program is capable of correcting small differences in the body shape and slope at the intersection of two differently shaped body sections.

The program will print out the supersonic portion of the flow field including the local body conditions and the conditions in the shock layer. Specifically, the velocity, flow angle, Mach number, entropy, pressure, enthalpy, and density are all printed out at each point in the supersonic flow field downstream of the sonic line.

Both perfect gas and equilibrium air real gas calculations can be handled.

D. Limitations

Both the perfect gas and real gas options of the method of characteristics program do not operate at flight Mach numbers below three ($M < 3$), as an embedded shock (intersection of characteristic lines) is developed in the flow field.

The program actually terminates when the characteristics become too close to one another, which physically represents the formation of a shock wave (embedded shock) which actually does not exist. This problem has been partially eliminated by decreasing the tolerance which determines whether characteristics have come close enough to consider that intersection of these characteristic lines has taken place. However, it

*Any additional expressions needed to describe a configuration can be easily added to the program.

is felt that this is due to a problem in the communications between it and the blunt body program. Therefore, it is suggested that revision of the technique utilized to obtain the starting line in the blunt body program be implemented to eliminate the embedded shock wave problem. In particular, it is suggested that one use:

- 1 A curved (concave) starting line
- 2 An unequally spaced starting line
- 3 Less than 16 points on the starting line.

Note: The starting line is generated by the blunt body program and is used subsequently to start the method of characteristics computer program.

E. Input

Input to the supersonic axisymmetric method of characteristics program consists of:

- 1 Free stream information
- 2 Sonic starting line data
- 3 A description of the missile configuration (body geometry).

This input can be supplied to the program in two ways:

- 1 The supersonic method of characteristics program can be run linked to the subsonic blunt body program; in this case the inputs required are the cards that describe the body geometry in addition to the cards necessary to run the blunt body program.
- 2 The supersonic method of characteristics program can be run separately. In this case additional cards must be supplied which describe the free stream conditions and the sonic starting line.

F. Output

The supersonic program output is the supersonic flow field. As the program progresses incrementally along the body, points on the characteristic lines from the body to the shock wave are printed out.

The output is headed by the free stream parameters. Sufficient information is printed out in the heading to identify the flight conditions. The flow field will then be filled in along the so called characteristic lines, from the body to the shock

wave. Each point is identified with a subheading denoting the point as a body point, shock point, or point on the characteristic. Each characteristic will have coordinates and flow quantities associated with it which are printed out.

Additional output will consist of all the above parameters along a line normal to the body axis at the x location of the first body point and those input stations requested. These lines are completed as the flow field is completed. The output is labeled FIELD VARIABLES NORMAL TO AXIS and gives velocity, flow angle, Mach number, pressure, enthalpy, density, and total pressure at points on the line for the particular x locations chosen.

The flow field will be filled in with characteristic lines until the end of body is reached; when this occurs, characteristic lines continue to be generated until the entire field between the body and the shock wave is complete.

Quantities related to drag are then computed (see Section V - Drag Calculation Subroutine). These quantities are pressure ratio, drag (lb), drag coefficient, and bluntness ratio (the ratio of the nose tip radius to the aft base radius). All these parameters are listed in tabular form according to (x, y) location along the body. Three plots are also obtained:

- 1 Body shape
- 2 Body station x versus pressure
- 3 Body station x versus drag coefficient.

The output parameters are:

$$X_i/R_b, X_i, Y_i/R_b, Y_i, P_i, P_i/P_\infty, D_i, C_{D_i}, 1/Y_i.$$

V. Drag Calculation Subroutine - Subroutine Dragon

The drag calculation subroutine computes the nondimensional pressure ratio (P/P_∞), the wave drag D, and the wave drag coefficient, C_{D_i} .

The drag force on the body is calculated by integrating the local body pressures over the appropriate corresponding areas. The equation used to compute the wave drag for the missile is:

$$D_i = D_{i-1} + \pi \left(\frac{P_i - P_{i-1}}{2} - P_\infty \right) \left(Y_i^2 - Y_{i-1}^2 \right) \frac{R_b^2}{144} \text{ lb}$$

where R_b is the nose radius in inches, and i and i-1 are two successive body points. The drag coefficient is calculated from the equation:

$$C_{D_i} = \frac{D_i}{q_\infty S_\pi}$$

where $q_\infty S_\pi$ is:

$$q_\infty S_\pi = \pi \gamma P_\infty M_\infty^2 Y_i^2 / 288 \text{ lb}$$

and Y_i is the aft radius (missile base radius).

To enable one to make a parametric study of nose blunting or missile length on drag, a cumulative tabulation of C_{D_i} was provided, where C_{D_i} is the drag coefficient for a missile of length X_i and aft radius Y_i .

The stagnation pressure is calculated for inclusion in the integration scheme, using the equation:

$$P_{stag} = \left[\frac{(\gamma+1) M_\infty^2}{2} \right]^{\frac{\gamma}{\gamma-1}} \left[\frac{(\gamma+1)}{2\gamma M_\infty^2 - (\gamma-1)} \right]^{\frac{1}{\gamma-1}}$$

It should be noted that this equation is only valid for the perfect gas option, and is an approximation for the real gas calculations. However, an effective γ based upon real gas properties can be used in the above equation to approximate the real gas stagnation pressure. Although this may be only a rough approximation to the real gas stagnation pressure, the effect of this approximation on the drag of the vehicle will be insignificant since this pressure is integrated over a very small area.

VI. Conclusions and Recommendations

A. Problem Areas

The computer program described in this paper has operated satisfactorily over a wide range of flight conditions and body geometries. The major problem area existing is the operation of the method of characteristics program at Mach numbers below three ($M < 3$). It is felt that this problem does not lie within the method of characteristics program, but rather in the communications between it and the blunt body program. Three suggestions were presented in Section IV for the revision of the technique utilized to obtain the starting line.

B. Areas of Future Work

Further checkout of the real gas program (for zero angle of attack) is required. A real gas model (on tape) was incorporated into the method of characteristics program. This gas model is an NBS (Hilsenrath and Beckett) model valid for temperatures up to 15,000°K. If for any reason it is later decided to employ a different gas model, the program can be easily implemented.

A sharp nosed body capability will be developed as an option to the program. Also, the possibility of incorporating a boundary layer option to compute the viscous interaction with the inviscid flow field is being considered. This would give full capability for providing entire flow fields for vehicles at zero angle of attack.

A three dimensional method of characteristics program for both sharp nosed and blunt nosed bodies with flares at angle of attack including viscous effects is presently under development.

VII. References

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